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Safety Analysis of an Airbag System using Probabilistic FMEA and Probabilistic Counterexamples

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***Abstract*—Failure mode and effects analysis (FMEA) is a technique to reason about possible system hazards that result from system or system component failures. Traditionally, FMEA does not take the probabilities with which these failures may occur into account. Recently, this shortcoming was addressed by integrating stochastic model checking techniques into the FMEA process. A further improvement is the integration of techniques for the generation of counterexamples for stochastic models, which we propose in this paper. Counterexamples facilitate the redesign of a potentially unsafe system by providing information which components contribute most to the failure of the entire system. The usefulness of this novel approach to the FMEA process is illustrated by applying it to the case study of an airbag system provided by our industrial partner, the TRW Automotive GmbH.**

I. Introduction

In light of the fact that a failure of a safety-critical system can lead to injuries and even loss of life it is extremely important to provide designers with safety assessment methods that help to minimise the risk of the occurrence of such disastrous events. One of these methods is *Failure Mode and Effects Analysis* (FMEA) [19]. In FMEA, a team of trained engineers or system designers analyses the cause-consequence relationships of component failures on system hazards. After having found such a relation, the occurrence probability of that hazard is computed. It is then checked whether this value is above a certain threshold, defined by the tolerable hazard probability or rate (THP or THR). If this is the case, measures must be taken to reduce the probability of the undesired event.

To support the traditionally time-intensive and error-prone FMEA, functional model checking techniques have been integrated into the FMEA process [7], [9], [10], [18], [15]. While these techniques are able to establish cause-consequence relationships, they are unable to calculate the actual failure probabilities. Therefore, stochastic model checking was applied to FMEA, leading to a *probabilistic FMEA* (pFMEA) process [13]. Currently, this pFMEA process provides no means to help the designer in reducing the risk of failures. It only supports the first step of the FMEA process, which is to identify cause-consequence relationships and compute the actual hazard probabilities.

The contributions of our paper can be summarized as follows:

- We illustrate the usefulness of pFMEA as supported by stochastic model checking using the real-life case study of an airbag system. We describe how to map the system architecture to a PRISM [22] model and illustrate how to perform pFMEA on this model. The airbag case study results from a collaboration with the automotive supplier TRW Automotive GmbH (in the sequel simply referred to as TRW) in Radolfzell, Germany, and is based on real data. Due to intellectual property concerns of TRW we are unable to publish the concrete values of component or overall system failure probabilities. This does not affect our finding that pFMEA can lead to useful failure probability assessment values, as confirmed by TRW.
- We address the inability of the current pFMEA method to give guidance on how to improve system dependability by integrating a recently developed technique for finding and visualising counterexamples in stochastic models. Counterexamples provide means to identify those parts that contribute most probably to the failure of the system and thus, provide valuable information for its redesign.

This paper is organised as follows: In Sec. II we will briefly introduce FMEA, pFMEA and counterexamples in stochastic model checking. Sec. III is devoted to the description of the airbag system and its PRISM model. In Sec. IV we will describe possible hazard conditions and system failures, and Sec. V is devoted to the probabilistic FMEA of the airbag system, supported by counterexample generation. In Sec. VI we compare our approach with existing approaches in the FMEA literature. Sec. VII describes the lessons learnt from this case study. Finally, Sec. VIII concludes the paper with a summary and an outlook on future research.

II. FMEA, pFMEA and Counterexamples

This section explains the basic concepts of the FMEA and its probabilistic extension pFMEA. In Sec. II-C we briefly introduce an approach to counterexample generation and visualisation for stochastic model checking.

A. FMEA

As described in the introduction, the aim of an FMEA is to explore the consequences, such as hazards, of known

component-level failure modes and to propose countermeasures to reduce the probability that these consequences occur. The final outcome of an FMEA is a table which documents for each component the set of relevant component failure modes, and for each of these failure modes its consequences. Possible failure detection, correction or mitigation mechanisms may also be recommended in this table. The structure, number of columns and meaning of columns of the resulting FMEA table may vary in different organizations performing FMEA. However, the following column headings are commonly used [19]: investigated component, failure mode, description of the failure mode/local effect of the failure mode, possible cause for the failure, effect at the system level, recommended failure detection mechanism, recommended mitigation mechanism, and recommended design changes. For complex systems with a large number of components and a large number of failure modes per component this table can become very large. Additionally, it has been reported in [16] that the table may contain redundant information since different failure modes can lead to the same consequences. The FMEA procedure is commonly defined by an iterative process [14] that identifies for all components the possible failure modes and identifies their consequences. Recent approaches [7], [8], [9], [10], [15], [18], [23] aim to support the FMEA process, especially the identification of possible consequences with model checking. The basic idea is to formalise the system's behaviour as a state-based model and the hazard conditions as temporal logical formulae. As a result, fault injection experiments can be created where specific failure modes are injected into the system behaviour model. Model checking tools can then analyse the consequences on the formalised hazard conditions.

B. pFMEA

A further development of the idea to use of model checking support for FMEA is the approach referred to as probabilistic FMEA (pFMEA) presented in [13]. Instead of functional state-based models pFMEA uses stochastic models, in particular discrete and continuous time Markov chains. The hazard conditions are formulated as stochastic temporal logical formulae. As a consequence the tolerable hazard probabilities can also be integrated into the formalisation of the hazard conditions. Furthermore, to each injected failure mode an occurrence probability can be assigned in the probabilistic model. A main benefit of pFMEA is the ability to probabilistically estimate the likelihood that an injected failure mode will lead to a violation of the hazard condition. The use of stochastic models also avoids a common shortcoming of using functional model checking in FMEA, namely that the model checker finds a relationship between the injected failure mode and a hazard that is very unlikely to occur in practice. As already noted in [13], one practical problem of pFMEA is the lack of counterexamples in stochastic model checking. This impedes the explanation of property violations and hence failure mode / consequence relationships found by the stochastic model checker.

C. Counterexamples in Stochastic Model Checking

In stochastic model checking, the property that is to be verified is specified using a stochastic variant of temporal logic. The temporal logic used in this paper is CSL (continuous stochastic logic) [5], [6]. It is tailored to reason about quantitative system behaviour, including the performance and dependability of a system. Given an appropriate system model and a CSL specified property, a stochastic model checking tool such as PRISM can verify automatically whether the model satisfies that property. If the model refutes the property, it is desirable to have a counterexample available that can help engineers to comprehend the reasons for the property violation. The computation of counterexamples in stochastic model checking has recently been addressed in [2], [3], [4], [17].

Notion of Counterexamples.: For our purposes it suffices to consider upper bounded properties which require the probability of a property offending behaviour not to exceed a certain upper probability bound. In CSL such properties can be expressed by formulas of the form $\mathcal{P}_{\leq p}(\varphi)$, where φ is path formula specifying undesired behaviour of the the system. Any path which starts at the initial state of the system and which satisfies φ is called a *diagnostic path*. A counterexample for an upper bounded property is a set X of diagnostic paths such that the accumulated probability of X violates the probability constraint $\leq p$.

Generation of Counterexamples.: In [2] it has been shown that counterexamples for this class of properties can be efficiently computed using an explicit state space search strategy called *eXtended Best-First* (XBF). XBF is a variant of Best-First search. XBF explores the state space of the model on-the-fly searching for diagnostic paths. It does not explicitly compute the counterexample path set X. Instead it incrementally computes a sub-graph of the state space which covers X called *diagnostic sub-graph*. Once the diagnostic sub-graph covers a sufficient number of diagnostic paths so that the accumulated probability exceeds the given upper probability bound, XBF terminates and produces the diagnostic sub-graph as a counterexample.

Counterexample Visualisation.: A counterexample is a potentially very large set of diagnostic paths. Although XBF provides the counterexample in the form of a sub-graph, it can still be very complex. Supporting the analysis of complex counterexamples using visualisation techniques is proposed in [3]. This approach aims at facilitating the discovery of causal factors for property violations. Portions of the model that contribute a larger portion of the probability mass to the property violation are brought out visually in order to support the discovery of causal dependencies.

The technique presented in [3] is designed for counterexample generation methods based on K-Shortest-Paths heuristic search algorithms like K* [4]. For the purpose of this paper we adopted that visualisation to be used in combination with XBF.

III. Case Study: Functionality and Modelling

A. System Functionality

Modern cars are equipped with safety systems, such as airbags, that protect the occupants of the vehicle. In case of a crash, the airbag system will deploy airbags located in different places in the car. They reduce the risk of serious or even fatal injuries for the occupants.

An airbag system can be divided into three major parts: sensors, crash evaluation and actuators. An impact is detected by acceleration sensors (front/rear/side impact) and additional pressure sensors (side impact). Angular rate or roll rate sensors are used to detect rollover accidents. The sensor information is evaluated by two redundant microcontrollers (μC) which decide whether the sensed acceleration corresponds to a crash situation or not. The deployment of the airbags is only activated if both microcontrollers decide that there was indeed a critical crash. The redundancy of the microcontroller system layout decreases the hazard of an unintended airbag deployment, which is considered to be the most hazardous malfunction of the system. Note that older airbag systems comprise only one microcontroller. Upon activation of the deployment, squibs are ignited and as a consequence the airbags are inflated by irreversible pyrotechnical actuators. The sensors can either be located as internal sensors inside the Airbag Electrical Control Unit, or mounted as satellites to the bumper, the a-, the b- or the c-pillar.

The airbag system architecture that we consider consists of two acceleration sensors whose task it is to detect front or rear crashes, either one microcontroller or two microcontrollers to perform the crash evaluation, and an actuator that controls the deployment of the airbag. Fig. 1 gives a schematic overview of the system architecture using the two microcontroller variant. Notice that the redundant acceleration sensors are pointing in opposite directions so that one (also referred to as *main sensor*) is measuring the acceleration in the x direction of the vehicle, and the other (also referred to as *saving sensor*) is measuring the acceleration in the $-x$ direction. The microcontrollers read the sensor values of the main and saving sensor (microcontroller 1) or the saving sensor (microcontroller 2) in a cyclic fashion. The two sensor values (x and -x acceleration) are compared after they have been read by microcontroller 1. They are then separately used for crash discrimination which is normally done by calculating mean values of the acceleration measured over certain intervals of time. If a certain threshold in a given time frame is exceeded, the microcontrollers will synchronise their fire decisions and only if they both come to the conclusion that a critical crash occurred the airbags will be deployed.

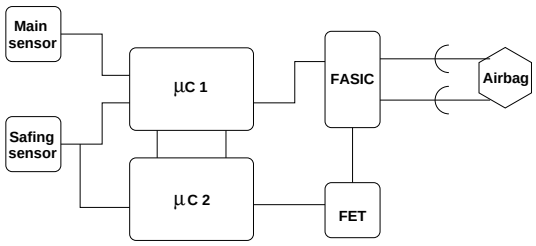

Figure 1. Schematic system architecture

The deployment of the airbag is secured by two redundant protection mechanisms. The Field Effect Transistor (FET) controls the power supply for the airbag squibs. If the Field Effect Transistor is not armed, which means that the FET-Pin is not high, the airbag squib does not have enough electrical power to ignite the airbag. The second protections mechanism is the Firing Application Specific Integrated Circuit (FASIC) which controls the airbag squib. Only if it receives first an arm command and then a fire command from the microcontroller 1 it will ignite the airbag squib. In case there is only one microcontroller, the signals from both the main and the saving sensor are evaluated by this microcontroller. The signals to both the FET and FASIC units are also only sent by this microcontroller.

Although airbags save lives in crash situations, they may cause fatal behaviour if they are inadvertently deployed. This is because the driver may lose control of the car when this deployment occurs. It is therefore a pivotal safety requirement that an airbag is never deployed if there is no crash situation.

B. System Model

The airbag system was modelled using the input language of the stochastic model checking tool PRISM [22]. The overall structure of the model corresponds directly to the system's architecture (cf. Fig. 1). The behaviour of each block and each bus or connection line, which may also be subject to failures, was modelled by a separate module in PRISM.

While modelling the airbag system, the following challenges had to be met:

1) Many failures stem from corrupted signals, which are of continuous nature. Continuous signals cannot be modelled in the PRISM language and we have to resort to abstractions by discrete approximations. The sensors convert the physical signals using an A/D converter to discrete signals whose values range from -512 to 511. Notice that for the system analysis it is irrelevant whether the original signal is corrupted or whether the corruption is due to an A/D converter failure. The obtained abstraction is, however, still too

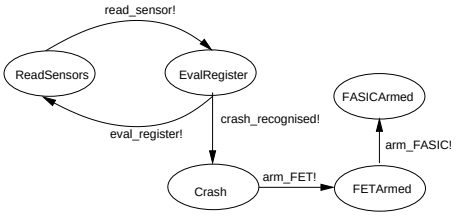

Figure 2. Basic microcontroller model

Figure 3. Basic FET model

Figure 4. Basic FASIC model

fine since the induced state space is beyond what could be handled by the PRISM model checker. We therefore abstract from the concrete values of the digital signals and only consider four categories of sensor values: a) normal driving, b) rear crash, c) frontal crash, and d) borderline cases (cf. Sec. IV). Due to space limitations, we can only consider cases a) and b) in this paper.

2) For the microcontrollers and the sensors we can safely abstract from internal behaviour, for instance from the failure of subcomponents, since these subcomponents are not manufactured by TRW. As a consequence, these failure modes fall outside of the responsibility of the organisation for which the FMEA is to be carried out. Instead, the total failure rate of the component that was determined by the supplier of these components is used. If these components turn out not to satisfy the reliability requirements, they need to be replaced in their entirety by other components.
3) The probability distributions for all failure rates can be safely assumed to be exponential. Either this assumption holds due to the data provided by the manufacturers of the components, or the distribution follows a bathtub curve [24] of which only the portion where the failure rate is constant is relevant. According to TRW, we can assume that the phases where the bathtub curve is not constant are either observed early in production and filtered out during the end of line testing, or they occur very late in the lifetime of the system where it can safely be assumed that the car is inoperative at that time.

Using these abstractions, we end up with a fairly accurate basis model (no failures, critical crash) that possesses approximately 55,000 states.

In Fig. 2 we present the state machine model of the microcontroller. ReadSensors is the system's initial state. Sensor values are read asynchronously from the sensors. The values are stored in registers and evaluated. If the sensor values indicate for n consecutive readings that a critical crash occurred, then the FET and the FASIC are armed, as indicated by the actions arm_FET! and arm_FASIC!, respectively. This reflects the fact that a critical crash has to be discriminated from innocuous high acceleration readings. For instance, when the car is driven over a curbstone or very fast in a curve or roundabout, high acceleration may be sensed for a very short period of time, leading to very few (less than n) high acceleration sensor readings. In this situation the airbag must of course not be deployed.

In Fig. 3 and Fig. 4 we present the basic state-machine model for the FET and FASIC modules with initial states WaitFET and WaitFASIC, respectively. The FET and FASIC synchronise with the microcontroller which sends commands to the FET and the FASIC using actions arm_FET? and arm_FASIC?, respectively. For the FASIC to finally fire, it synchronises with the FET via the action fire_FASIC?, which is sent by the FET unit (fire_FASIC!).

IV. System Failures and Hazard Conditions

We describe possible failures of the system components and their respective consequences for the safe functioning of the system. Hazards consist of unintended airbag ignition and suppressed or delayed airbag ignition in the case of a crash.

A. System Hazards and Safety Requirements

According to the upcoming ISO standard 26262 [21], which is an adaption of ISO 61508 [20] for road vehicles, new airbag systems have to comply with ASIL D (Automotive Safety Integrity Level D) for unintended deployment of the airbag. ASIL D corresponds to a tolerable hazard rate (THR) of 10^{-8} per hour. Currently, airbag systems are only required to comply with ASIL B which specifies a THR of 10^{-7} per hour. For our case study, we found the following hazard conditions to be relevant (specified in CSL using the Probabilistic Existence pattern from [12]):

1) The airbag is not ignited even though a critical crash occurred. This hazard can be formalised as safety requirement 1 in CSL as follows:

$$\mathcal{P}_{\leq p_1}(\mathsf{true}\ \ U^{>T_1}\ \ (\mathsf{critical\_crash} \wedge \neg \mathsf{fasic\_fired})).$$

For the purpose of the analysis we let the probability bound $p_1 = 10^{-3}$ and the actual time bound $T_1 = 20\ ms$. critical_crash and fasic_fired are atomic properties that can be derived from the original PRISM model. critical_crash is the state of the microcontroller in which, after reading and evaluating the sensor values, it is decided that the crash event requires airbag deployment. fasic_fired is the state of the FASIC module which indicates that the FASIC finally sent the fire command to the airbag squibs.

2) The airbag is ignited at latest after $T_2 = 45\ ms$, which yields safety requirement 2:

$$\mathcal{P}_{\leq p_2}(\mathsf{true}\ U^{>T_2}\ (\mathsf{critical\_crash} \wedge \mathsf{fasic\_fired}))$$

With this hazard condition, we associate a tolerable violation probability p_2 of 10^{-4}.

3) The airbag is deployed unintentionally, which means that it is ignited even though no crash at all or only a non-critical crash has occurred. This leads to safety requirement 3 in CSL:

$$\mathcal{P}_{\leq thp_3(T_3)}(\mathsf{true}\ U^{\leq T_3}\ (\neg\mathsf{critical\_crash} \wedge \mathsf{fasic\_fired}))$$

This hazard is associated with a tolerable hazard probability (THP) $thp_3(T_3)$ which depends on the mission time T_3, and the THR associated with the desired ASIL D:

- Given the mission times $T_3 = 1\ hr$, $5\ hrs$, and $10\ \ hrs$ and using ASIL B we obtain: $thp_3(1\ hr) = 1.0{\cdot}10^{-7}$, $thp_3(5\ hrs) = 5.0{\cdot}10^{-7}$, and $thp_3(10\ \ hrs) = 1.0 \cdot 10^{-6}$. The actual THP can be computed according to the formula $THP(t) = 1 - e^{-THR \cdot t}$, where t is the mission time (here: driving time).
- Similarly, for ASIL D, we obtain: $thp_3(1\ hr) = 1.0 \cdot 10^{-8}$, $thp_3(5\ \ hrs) = 5.0 \cdot 10^{-8}$, and $thp_3(10\ h) = 1.0 \cdot 10^{-7}$.

B. Sensor Failures

For the sensors, we have identified the following failure modes:

1) Even though both sensors measure the same signal, the amplitude of this signal at both sensors is different.
2) The sensors deliver wrong amplitudes. This means that the amplitude of the real signal is corrupted by sensor failures.
3) The sensors function correctly, but since the sensor values are not sampled synchronously the delay between the two samples may be so large that the amplitudes are erroneously interpreted as being different.
4) Both sensors are accelerated in the same direction. This means that the amplitudes on both sensors have the same prefixes.

C. Microcontroller Failures

As we argued above, for the purpose of this FMEA we treat the microcontroller as an atomic system component and do not consider its internal failure behaviour. The potential consequences of a failure of one of the microcontroller components are:

- A fire command is needlessly sent to the FET and FASIC, thus causing an unintended deployment of the airbag.
- A fire command in case of a critical crash is suppressed, thus preventing the airbag from being ignited.
- The fire command for the airbag in case of a crash is delayed, thus causing the airbag to be ignited too late.

According to TRW, the first case is considered to be the most hazardous scenario.

D. Power Supply Failures

The power supply unit has two lines: a 5V-line connected to the microcontroller and the sensors and a 24V-line to the FET- and FASIC-units. Both lines are subject to failures:

1) 5V-line: If the voltage of this line is above a certain threshold a number of causally dependent failures can occur:
   - Both sensor amplitudes have the same value which means that the sensor signals are corrupted, and
   - the firing lines of the microcontroller can be set needlessly to high.

   If the voltage is below $4V$, then the airbag system will be set to the inactive mode, which is indicated by a warning lamp. This can be considered to be a safe operational mode.
2) 24V-line: We distinguish two failures that may lead to hazardous situations:
   - If the voltage is too high, for instance above 40V, the FET and FASICs may be destroyed.
   - If the voltage is between 7 and 19V, the airbag system is in a degraded operational mode.

   If the voltage of this line is below 7V, the airbag system is inactive which means this is a safe operational mode.

E. FET Failures

The FET can be compared to a switch. It can either be closed inadvertently and hence enable the FASIC to fire, or it can be open instead of being closed as requested and hence suppress ignition of the airbag.

F. FASIC Failures

The FASIC consists of two internal switches (High-side and Low-side switch).

1) It is possible that either one or both of these switches close inadvertently, or that one or both of them do not close as requested. In the first case, an ignition of the airbag is not possible as long as the FET is not activated. In the latter case a correct firing may be suppressed by the FASIC.
2) For diagnostic purposes the FASIC is connected to the voltage supply. If this line is connected to the output line of the FASIC due to an internal short circuit, the FET protection becomes useless and the airbag may be fired.

G. Bus/Connection Line Failures

Due to environmental conditions the connection lines from the sensors to the μC and the busses from the μC to both the FET and FASIC in the airbag system are subject to failures. These signals can be corrupted, thus potentially violating all three safety requirements.

H. Component Failures

The failure mode matrix that describes the change from fault-free to faulty behaviour is modelled as a PRISM module. In case of single component failures, it consists of a single transition, from normal behaviour (failure mode fm 0) to the failure mode n under consideration ($n = 1...10$, cf. Table I).

In case of multiple-component failures, this module becomes more complex, for example, for microcontroller and FASIC failure, we obtain the following failure mode transition matrix encoded in PRISM:

```
module FailureViewMatrix
fm:[0..11] init 0; //Ten basic failure modes //
//combined failure modes are assigned a fresh value //
[] fm = 0 -> rate_MCFailure:(fm' = 3);
[] fm = 0 -> rate_FASICFailure:(fm' = 6);
[] fm = 3 -> rate_FASICFailure:(fm' = 11);
[] fm = 6 -> rate_MCFailure:(fm'=11);
```

The expressions fm = ... denote the transition guards in which the current failure mode is checked. The respective transition can only fire if the guard condition is satisfied. In the course of a transition the failure mode is set to a new value, for instance from 0 to 3 when taking the first transition. In the case of intermittent failures (sensor or bus line failures can be of that kind in this case study), transitions back to failure mode 0 have to be added. For all other components, such as FET, FASIC and microcontroller, failure recovery is not considered.

The failures are injected into the basic model by adding transitions that model the effect of the failure to the respective component. These transitions can only be taken if the system is in the corresponding failure mode. The transitions which model the failure-free module behaviour can also only be taken if the failure under consideration has not yet occurred.

For example, consider the potential microcontroller failure of suppressing a fire command in case of a critical crash. This scenario is important for safety requirements 1 and 2 (cf. Sec. IV-A). In case of a failure (fm = 3), in the worst case, the fire signal is not sent, represented as transition from Crash back to ReadSensors, labelled with $\mathsf{fm} = 3/\mathsf{skip}!$. A simple state machine representation of this model can be found in Fig. 5. If the microcontroller fails such that the signal is delayed, this is modelled by assigning a smaller rate to the fire-command-transitions. Since no real data for this situation exists, TRW suggested to use half the rate that is applied in case of normal operation.

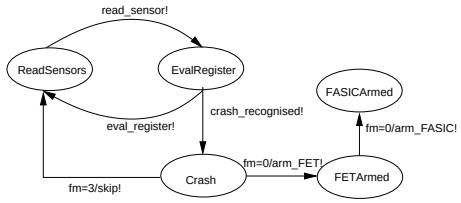

Figure 5. State machine representation of microcontroller with injected failure

When a failure of the microcontroller results in a needless deployment of the airbag (relevant for safety requirement 3), the fire command is sent even if no crash is recognised. In Fig. 6 this situation is shown, by a transition labelled with $\mathsf{fm} = 3/\mathsf{skip}!$ from the initial state ReadSensors to the state Crash.

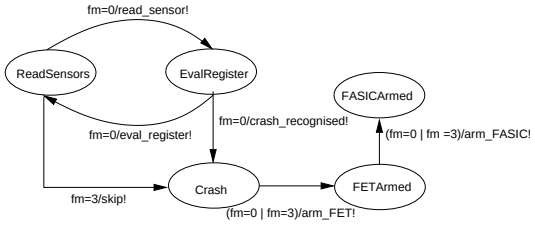

Figure 6. State machine representation of microcontroller with injected failure

V. Probabilistic FMEA of the Airbag System

In order to perform the pFMEA we conduct model checking experiments by injecting faults into the PRISM system model[1]. Thereby, we proceed as described in detail in [13]. The injected faults are as described in Sec. IV. Faults can be single or joint faults. In other words, more than one component can fail at a time.

A. Scenarios

To conduct the experiments, we assume that there is an environment which models the possible driving scenarios that there is 1) no crash, and 2) a frontal crash. For the first scenario the relevant hazard condition is the unintended ignition of the airbag. For the second scenario we are interested in the probability of a timely airbag ignition. Each scenario is considered in isolation as the analysis results would be useless otherwise. We are interested in the probability that the safety requirements from Sec. IV-A are violated. If all possible scenarios were merged into a single model, such an analysis would be impossible.

[1]A sanitized basic PRISM model with no accident as well as a FET failure model can be downloaded from the following URL: http://www.inf.uni-konstanz.de/soft/research/projects/pFMEA/pFMEA-PRISM.zip.

B. Failure Modes and Experiments

For our analysis, we have identified one normal operation mode, which is referred to as Fm_0, and ten failure modes, Fm_1 to Fm_{10}. A short description of the failure modes can be found in table I. While the official safety requirements

Failure view	Description
Fm_0	Normal operation
Fm_1	Sensor failure: Different amplitudes
Fm_2	Sensor failure: Amplitudes wrong
Fm_3	Summary failure of any microcontroller component
Fm_4	Power supply failure
Fm_5	FET failure
Fm_6	FASIC failure
Fm_7	μC-FET-line failure
Fm_8	μC-FASIC-line failure
Fm_9	Main sensor-line failure
Fm_{10}	Saving sensor-line failure

Table I
FAILURE MODES

standards only consider single failures it is possible in principle to experience simultaneous multiple component failures. Since our analysis approach is automated, we can easily accommodate multiple component failures and hence consider the following combinations: 1) power supply- and microcontroller-failure, 2) FET- and FASIC-failure and 3) microcontroller-, FET- and FASIC-failure. Table II presents the results of the pFMEA for 2 microcontrollers in case of a critical frontal crash for the safety requirements 1 and 2 from Sec. IV-A that are the relevant safety requirements for this scenario. We only considered failure modes Fm_0, Fm_1, Fm_3, Fm_4, Fm_6, and Fm_9. Where applicable, we have taken both permanent and intermittent failures into account. The system with one microcontroller also complies with ASIL D for safety requirements 1 and 2.

We checked safety requirement 3 with varying time bounds for the case in which no critical crash occurs. We first analysed the one-microcontroller architecture and checked whether it complies with ASIL D. ASIL D cannot be satisfied in all cases with this architecture. In the case of a combined microcontroller and power supply failure, with $T_3 = 5$ and 10 hours mission time, the actual hazard rate was slightly above the THR. Therefore, the experiments

	Requirement 1	Requirement 2
	violated (yes/no)?	
Fm_0	no	no
Fm_1, permanent failure	no	no
Fm_1, intermittent failure	no	no
Fm_3	no	no
Fm_4	no	no
Fm_6	no	no
Fm_9, permanent failure	no	no
Fm_9, intermittent failure	no	no

Table II
ANALYSIS RESULTS IN CASE OF A FRONTAL CRASH (2 MICROCONTROLLERS, ASIL D)

	$T_3 = 1h$	$T_3 = 5h$	$T_3 = 10h$
	Requirement 3 violated (yes/no)?		
Fm_0	no	no	no
Fm_1, per. failure	no	no	no
Fm_1, int. failure	no	no	no
Fm_3	no	no	no
Fm_4	no	no	no
Fm_6	no	no	no
Fm_9, per. failure	no	no	no
Fm_9, int. failure	no	no	no

Table III
ANALYSIS RESULTS FOR REQUIREMENT 3, NO CRASH (2 MICROCONTROLLERS, ASIL D)

	$T_3 = 1h$	$T_3 = 5h$	$T_3 = 10h$
	Requirement 3 violated (yes/no)?		
Fm_3 and Fm_{10}	no	yes	yes
Fm_5 and Fm_6	no	no	no
Fm_3, Fm_5 and Fm_6	no	yes	yes

Table IV
ANALYSIS RESULTS FOR REQUIREMENT 3, NO CRASH, MULTIPLE FAILURES (1 MICROCONTROLLER, ASIL D)

were repeated with a model of the airbag system with two microcontrollers. The results of this experiment can be found in table III.

C. Multiple Failures and Counterexamples

We now consider the actual hazard rate for multiple failures, even if this is not required by the standard. We believe that it is important to go beyond the minimum safety requirements specified in the standard in order to design reliable safety critical systems.

While the airbag system with only one microcontroller complies with ASIL B, it does not comply with ASIL D in the case of multiple failures. We noticed that when microcontrollers and FET and FASIC failures occurred the actual hazard rate is significantly above the THR (cf. Sec. IV-A). In table IV we can find the results of the pFMEA analysis in case no accident occurs while considering multiple component failures. Therefore, we generated counterexamples for these cases in order to identify the primary source of the safety requirement violation. For 2 microcontrollers the actual hazard probability complies with the upcoming ASIL D.

Counterexample Support for pFMEA.: Due to space limitations, we can only discuss the case in which the microcontroller, FET and FASIC can fail. This case is interesting for the following reasons: First, the FASIC is the least reliable component. Second, the microcontroller is the central part of the system, and the correct airbag ignition depends heavily on the results delivered by the microcontroller. It is therefore interesting to check what weighs more in the violation of the ASIL D property, the reliability or the potential consequences of a failure. Intuitively, one might expect that the FASIC failure contributes more to the violation of ASIL D than a microcontroller

failure. The computation and analysis of the counterexample, however, reveals that in fact the microcontroller failure is more critical. Based on these findings, a solution that reduces the impact of a microcontroller failure is to be preferred over making the FASIC more reliable. TRW does indeed follow this finding by introducing a second microcontroller into the airbag architecture, thus alleviating the consequences of a single microcontroller failure. A second interesting finding of the counterexample analysis is the fact that multicomponent failures are highly improbable. For further analyses they hence do not need to be considered, which results in models with a much smaller state space.

The execution traces of the system leading to states in which component failures causes an erroneous airbag ignition can be represented in a purely textual way. Since there is potentially a very large number of such traces, the user would have to browse many of them until the desired information which component failure contributes most to the property violation has been recognized. In order to facilitate this task we propose to present a visualization of the error traces. In Fig. 7 we show the visualisation of a portion of the error traces of the airbag system model. Note that this figure only contains a very small excerpt of the entire state space graph that we use to explain the basic principle of the visualization. A more complete view can be found in [1]. To visualize the full graph we need to rely on high resolution devices.

Error states in Fig. 7 are represented by diamond-shaped rectangles with red lines. The more probable it is to be in such an error state, the larger the state is depicted. We can see that the state representing a microcontroller failure is much larger than any other state. Which state corresponds to which failure mode can be read from the transition labels. According to Table I, a microcontroller failure corresponds to a transition with label Failuremode3, a FASIC failure corresponds to a transition with label Failuremode6, and combined FET and FASIC failures corresponds to a trace in which both Failuremode5 and Failuremode6 labelled transitions can occur.

D. Time and Space Complexity of Model Checking

The sizes of the models we encountered vary from 1,536 states for failure mode 0 and no crash to 615,600 states for failure mode 2 with intermittent failures and crash. The largest model only required 28.4 MB of storage, including iteration vectors for the numerical analysis. Memory consumption hence was not a problem during the analysis.

While in the case of safety requirements 1 and 2 the model checking is very efficient despite large state spaces, it can be seen that in case of safety requirement 3 the runtimes increase steeply. For the failure mode 2 model with intermittent failures, having 615,600 states and requirement 2, model checking took only 311 sec., whereas for safety requirement 3 and a mission time of 10 h for the same model, the model checking time exceeded 12 hours. This enormous increase can be explained by the fact that in the latter case the time bounds are extremely high in comparison to safety requirements 1 and 2. This runtime increase occurs since, amongst other factors, the number of iterations for transient analysis is determined by this value.

Approach & Year	**Spec. Formalism**	**Tool**	**Prob. FMEA**	**Counter-examples**	**Case Studies**
Heimdahl et al. 2005[18]	RSML^{-e}	NuSMV	No	Yes	Altitude Switch
Bozzano et al. 2003 [7]	NuSMV code	FSAP/ NuSMV-SA	No	Yes	Bit Adder
Cichocki & Górski 2000[9], [10]	CSP	FDR	No	No	Line Block System
Grunske et al. 2005 [15]	Behavior Trees	SAL	No	Yes	Metal Press
Elmqvist & Nadjm-Tehrani 2008 [11]	PRISM Reactive Modules	PRISM	Yes	No	Altitude Meter System
Grunske et al. 2007 [13]	PRISM Reactive Modules	PRISM	Yes	No	Metal Press
Our Approach	PRISM Reactive Modules	PRISM	Yes	Yes	Industrial case study (airbag system)

Table V
COMPARISON WITH RELATED APPROACHES

VI. RELATED WORK

A considerable number of approaches have been proposed to automate or support the FMEA process with model checking [7], [8], [9], [10], [15], [18], [23]. The existing approaches are summarised in Figure V. From this comparison it becomes evident that only the approaches described in [11] and [13] use probabilistic model checking and support a probabilistic FMEA process. All other approaches work with traditional model checking tools. The novel aspect described in this paper with respect to the approaches in [11] and [13] is the support (generation and analysis) of counterexamples. These counterexamples provide valuable insights in the cause-consequence relationships between low level component failures and system level hazards. Furthermore, while all the existing approaches only work with small academic examples, a central contribution of this paper is to provide evidence that the process scales to an application taken from an industrial product development context.

VII. LESSONS LEARNT

System Modelling.: With respect to system modelling, we have learnt the following lessons: First, even though PRISM is not designed to model continuous signal processing we were able to devise a suitable discrete state

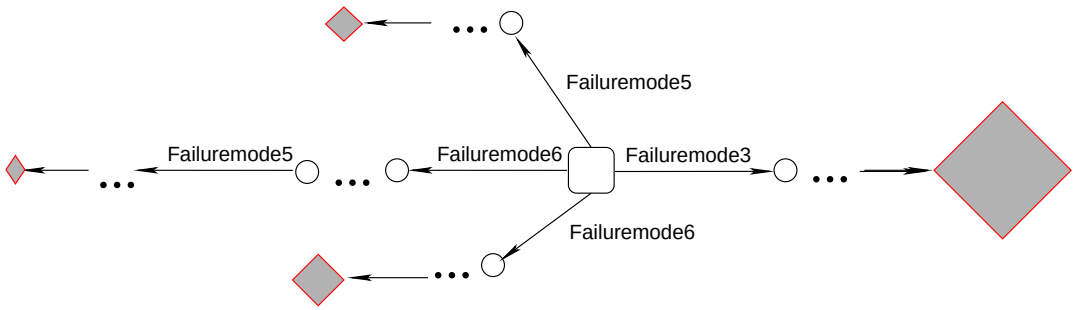

Figure 7. A portion of the counterexample visualisation in the case of μC, FET and FASIC failures

machine abstraction of the signal generating process. Using this abstraction we could model crash events with a state machine with only five states. TRW confirmed that this abstraction is adequate and does not negatively influence our findings.

Second, it is interesting to realize that the state space size or structure is not the only limiting factor for the applicability of stochastic model checking. We had to deal with large time bounds. Time bounds influence the number of iterations needed for transient analysis. Even for the moderate size models that we encountered the runtime cost for numerical analysis may become prohibitive. This is an observation that appears to more generally apply to the analysis of safety critical systems that have long mission times.

Third, we learnt that PRISM is a language that the engineers at TRW could quickly learn. The logic CSL itself, however, was considered to be rather "exotic". A pattern-based approach as, for example suggested in [12], may help the further proliferation of pFMEA in the industry.

Implications for Industry.: There are a number of potential benefits from the adoption of probabilistic FMEA in industry. First of all, pFMEA is a means to to analyze with a reasonable effort which reliability requirements are satisfied by an *existing* state of the art design. In this case, we saw that although an existing single path airbag system is reliable in the field, not all new safety requirements are fulfilled. This result confirms the decision of TRW that in order to fulfill all safety requirements, future systems have to be built with two redundant paths to increase the reliability.

Second, probabilistic FMEA is a technique that can be used at the early stages of the system development process to evaluate the reliability of a *newly* designed system and to identify weak paths with a high failure probability in the architectural design. The upcoming standard ISO 26262 defines the goal to decrease the number of unintended behaviour of electronic components in the car and it requires the assessment of design alternatives to find the one that is the most reliable. The proposed approach facilitates and supports this assessment and provides a basis for the technical discussion and comparison of design alternatives.

Third, due to the fact that the analysis is automated and supported by tools it is possible to investigate much more complex scenarios than with a manual analysis, such as for instance multiple failures.

VIII. Conclusion

We have presented a case study for applying probabilistic FMEA to an industrial airbag system. The system was modelled and analysed using the PRISM tool. By applying probabilistic FMEA, two system configurations were checked for compliance with the upcoming safety standard for road vehicles ASIL D with respect to a large number of possible component failures. For the system variant with one microcontroller, we found the ASIL D requirements to be violated. Using counterexample generation and visualisation, we were able to identify the main source of the requirement violation.

Although the research presented in this paper provides evidence of the applicability of the pFMEA process to industrially relevant systems, improvements to the performance of probabilistic model checking and counterexample generation algorithms as well as improved counterexample presentation and visualization methods would in particular further enhance the applicability of the pFMEA process.

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